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Comments Regarding FCC 03-110

Revision of Parts 2 and 15 of the Commission's Rules to Permit Unlicensed National Information Infrastructure (U-NII) Devices in the 5 GHz Band

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1. Introduction

The Federal Communications Commission (FCC) has released a notice of proposed rulemaking FCC 03-110 [1] as of June 4, 2003. This notice pertains to making an additional 255 MHz of bandwidth available in the 5.47 – 5.725 GHz band for the operation of unlicensed National Information Infrastructure (U-NII) devices including Radio Local Area Networks (RLANs).

While applauding this additional allocation of spectrum resources for use by U-NII devices, this memorandum seeks to provide additional provisions for the use of the U-NII spectrum that will benefit all users of these rare resources.

2. Background

Under the current FCC Part 15 rules, U-NII devices are permitted to operate in a total of 300 MHz of spectrum in the 5.150 - 5.250 GHz, 5.250 – 5.350 GHz and 5.725 – 5.825 GHz bands. The technical and operational requirements are different in each of these bands. The newly proposed bandwidth allocation of 5.47 – 5.725 GHz fits in nicely between the pre-existing upper two U.S. frequency bands making for nearly contiguous coverage from 5.150 – 5.825 GHz.

Other countries, notably Japan, may allocate U-NII type spectrum at lower frequencies (e.g., 4.9 – 5.0 GHz) which will lead original equipment manufacturers (OEMs) to most likely develop silicon chipsets that cover 4.9 – 5.9 GHz in one product.

Only a handful of companies are shipping 5 GHz RLAN products (e.g., IEEE802.11a) in any significant volume at the present time and spectrum congestion issues are therefore quite minimal. However, it is very likely that many of the same problems that presently plague the 2.4 GHz RLAN frequency band will migrate to the 5 GHz band unless some additional considerations are attended to.

Historically, the 2.4 GHz RLAN activity has been largely data-only in nature where best-effort communication links have been both successful and adequate to serve most applications. In best-effort RLAN communication links, no quality of service (QoS) is guaranteed. Without a QoS guarantee, the effective data throughput rate may only be a small fraction of the actual signaling rate due to the data re-transmissions that arise from data errors and collisions[1] with other terminal devices trying to use the same RF channel. Since each data packet may have to be re-transmitted an arbitrary number of times before it is finally communicated across the wireless link without error, the time required for any specific data packet to successfully traverse the wireless link can vary dramatically. This time "jitter" is very harmful to audio and video (A/V) applications and the frequent re-transmissions involved also consume channel throughput resulting in poor utilization of the valuable RF spectrum available.

Many consumer electronics (CE) companies are interested in using RLAN techniques in the 5 GHz frequency band to transport A/V content wirelessly. Many companies have tried unsuccessfully to use CSMA-based RLAN techniques in the 2.4 GHz band for these A/V purposes because of the inherent absence of QoS in CSMA-based systems. In addition, the 2.4 GHz band has posed additional issues for A/V applications due to the interference from microwave ovens, cordless phones, etc. that can equally degrade QoS performance significantly.

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1 Not all RLANs suffer collisions between multiple terminals trying to use the same RF channel. IEEE802.11 networks use an asynchronous medium access control (MAC) technique known as carrier sense multiple access with collision avoidance (CSMA/CA). Synchronous MACs like HiperLAN2 avoid collisions of this nature by highly orchestrating the RF channel usage through the allocation of assigned time-slots, traditionally known as time division multiple access (TDMA).

The future of the 5 GHz spectrum can be dramatically enhanced for both CE and data applications if additional guidelines are provided in the FCC rules. This memorandum addresses some of the features that would be most helpful in this regard.

3. Discussion

Everyone recognizes that RF spectrum resources are rare and that they should be used as efficiently as possible. This is particularly true in the 5 GHz band where the IEEE802.11a and HiperLAN2 specifications use 20 MHz wide channels. Consequently at the present time, there are only 4 channels available in Japan and 8 channels available in the 5.15 – 5.35 GHz portion[2] of the U-NII band in the United States.

One of the most exciting and lucrative emerging market opportunities involves wireless home networks that are used for distributing high-quality audio and video throughout a home. Unlike wireless networking of the past, these entertainment networking activities require QoS characteristics that cannot be reliably delivered using traditional CSMA-based[3] networking. It is crucial that the traditional CSMA based networks and the newer TDMA-based networks adopt terminal characteristics that permit the co-existence of both network types if these new market opportunities are to successfully evolve. This same co-existence objective also translates into substantially better utilization of the rare spectrum resources available for all users, CSMA- and TDMA-based alike, than if no improvements are made.

Two of the most basic improvements that should be added are (i) dynamic transmit power level control and (ii) dynamic frequency selection (DFS). As described herein, these features are crucial improvements that need to be made for operation in the domestic 5 GHz band, both for improving network performance as well as keeping pace with the rest of the world. The absence of these two capabilities in the IEEE802.11a standard is a major reason why equipment based upon this standard is not allowed to operate in Europe[4].

One of the baseline assumptions made in FCC 03-110 [1] was that original equipment manufacturers (OEMs) will be forced to redesign their 5 GHz equipment over a period of time in order to (i) make use of the proposed new frequency band allocation and (ii) to comply with the proposed spectrum monitoring rules to avoid interference with other primary services that share the same regions of the RF spectrum. It is only appropriate then that other measures be included in this rulemaking activity if they lead to better utilization of the RF spectrum at a reasonable cost and complexity point. Recommendations in this regard are provided in the sections that follow.

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[2] The lower two 100 MHz frequency bands are generally considered more desirable for indoor applications, leaving the 5.725 – 5.825 GHz band for outdoor (high-power) applications.

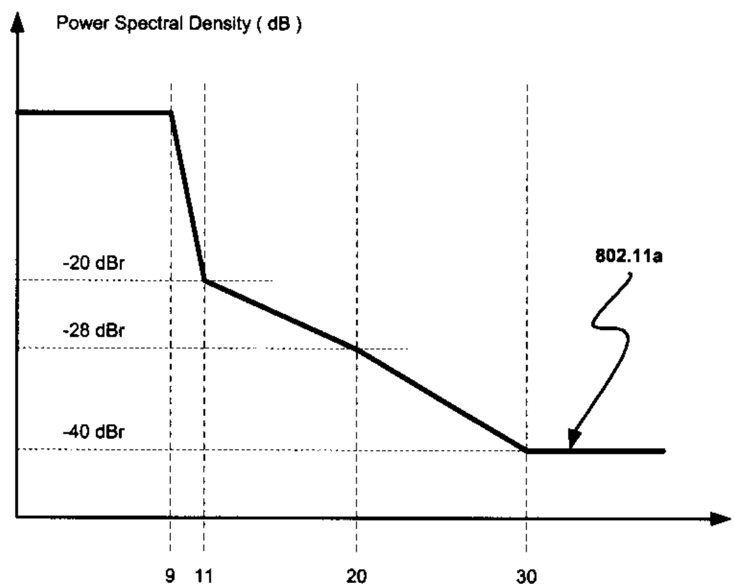
[3] CSMA-based networks offer unbounded QoS in that the arrival time of a given data packet at the destination terminal can vary widely in time thereby introducing time "jitter".

[4] The physical layer portion of the European HiperLAN2 standard is almost identical to the IEEE802.11a standard except for the inclusion of these two major features. The HiperLAN2 system also uses a TDMA-based MAC whereas IEEE802.11a is CSMA/CA-based.

3.1 Transmitter Output Spectral Purity

The present IEEE802.11a standard stipulates that the transmit spectrum fall within the mask provided here in Figure 1. The spectral region of greatest interest here is for frequency offsets greater than 30 MHz where the noise floor is required to only be < -40 dBr.

Figure 1 IEEE802.11a Transmit Spectrum Mask (One-Sided)



The transmit spectrum mask shown in Figure 1 can be broken into three distinct regions: (1) the main lobe having frequency offsets < 9 MHz, (2) the spectral re-growth region having frequency offsets from 9 MHz to 30 MHz, and (3) the ultimate transmitter noise floor having frequency offsets greater than 30 MHz. The spectral re-growth region results primarily from odd-order nonlinearities within the transmit chain, most significantly the output power amplifier (PA), along with some spectral-broadening due to the phase noise performance of the radio's frequency synthesizer.

One of the primary concerns involved with the transmitter spectrum noise floor requirement provided in Figure 1 is that the transmitter is allowed to transmit a fairly high noise floor over an arbitrarily wide frequency spectrum thereby potentially interfering with one or more other networks that may be in the same general vicinity.

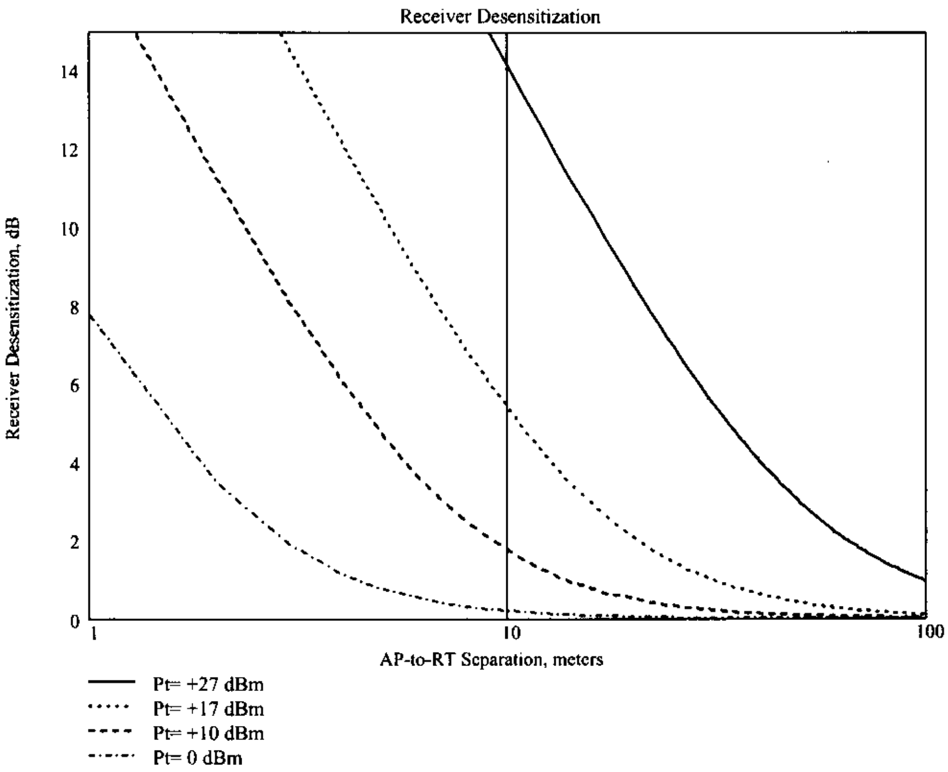
As shown in Figure 2, the –40dBr transmit noise floor (Figure 1) will result in potentially serious system receive sensitivity loss depending upon (a) the transmitter output power level being used and (b) the distance between the two networks involved. Since the transmitter noise floor is allowed to be arbitrarily wide across the 5 GHz band per Figure 1, this serious interference can result regardless of the RF channels being used by different networks and is therefore very undesirable.

Example 1:

Assume that one RLAN is operating in condominium A on a channel center frequency of 5.200 GHz. Assume that a second RLAN is also operating in nearby condominium B on a channel center frequency of 5.320 GHz. Under present FCC rules, both RLANs could be transmitting at their maximum-allowable power levels of 40 mW and 200 mW respectively even though only a small fraction of these power levels may actually be required to deliver good link quality within each respective condominium. As shown in Figure 2, if network terminals in the two condominiums are effectively only 10 meters apart, the noise level inflicted by each terminal on the other terminal could degrade the receiver sensitivities from 6 to 14 dB. At a minimum, both networks are forced to operate at higher transmit power levels to try and overcome the interference. Worst case, the interference between the two networks could be so high that only the slowest signaling rates can properly operate regardless of the transmitter power level used or the frequency channel separation employed.

The technical details for this section and the supporting details for Figure 2 are provided in Section 7 and Section 8 respectively. Receiver desensitization beyond 1 to 2 dB should be considered fairly serious since 6 dB represents a communication range reduction by one-half under free-space propagation conditions.

Figure 2 RT Sensitivity Loss Due to IEEE802.11a Allowable Transmit Noise Floor Versus Range



Such scenarios easily occur in apartment complexes, condominium complexes, and enterprise situations where potentially many disjoint 5 GHz networks could be operating simultaneously.

Interference levels could be large enough to prevent communication at the highest IEEE802.11a signaling rates regardless of the receive signal strength within a given network. Regardless whether a network is CSMA-based or TDMA-based, the performance of both networks are compromised unless greater efforts are taken to mitigate interference from other nearby networks. The interference issues between nearby networks becomes proportionally worse as (i) higher transmit power levels are used and (ii) as the distances between terminal devices belonging to different networks is reduced.

Example 2:

Assume that a 2-story apartment complex has one center hallway with adjacent apartments along both sides of the hallway. Apartments with individual square footage of 1000 square-feet are quite common. Further assume that the width of each apartment along the hallway is 30 feet and the depth of each apartment is 33 feet. In this scenario, 10 other apartments are within roughly 30 feet of any other apartment. If the RLAN networks within each apartment are allowed to operate at any power level resembling "full-power" (e.g., +17 dBm) with no additional power-level control or transmit spectrum improvement beyond present requirements, the transmit noise floor of every RLAN device will present interference to every other network within any where from 50 feet to 150 feet in distance. With the broad-band noise permissible from each transmitter, relatively few networks could produce severe performance problems.

Example 3:

Assume that multiple CE companies simultaneously demonstrate their wireless products at CES next year. Since the display booths have minimal RF-absorbing walls present and convention halls have fairly high ceilings, propagation characteristics may exhibit far less attenuation than that experienced in most homes. As a result, existing IEEE802.11a devices that always transmit at "full-power" (e.g., +17 dBm for example) could have a spectrum noise "footprint" that spans several hundred feet in diameter within the exhibit hall. The same spectrum issues discussed earlier could lead to many performance problems for exhibitors who are unfortunate enough to be "close together" in the exhibit hall, let alone the public's possible inference that wireless home networking is not reliable.

The solution to this problem is to (i) impose tighter spectral requirements on the noise sidelobes permitted from the transmitter for frequency offsets greater than approximately 30 MHz, and to (ii) impose transmit power level control so that each network only uses the amount of transmit power required to cover its network. Both of these topics are addressed further in the sections that follow.

> Potentially severe interference between independent networks operating within close proximity like those encountered in apartment and condominium complexes can only be reduced by (i) imposing more stringent transmit spectrum requirements on the terminal devices and (ii) by dynamically adjusting the transmit power level for each network link such that the minimum power level needed for the respective data throughput rate and range is used.

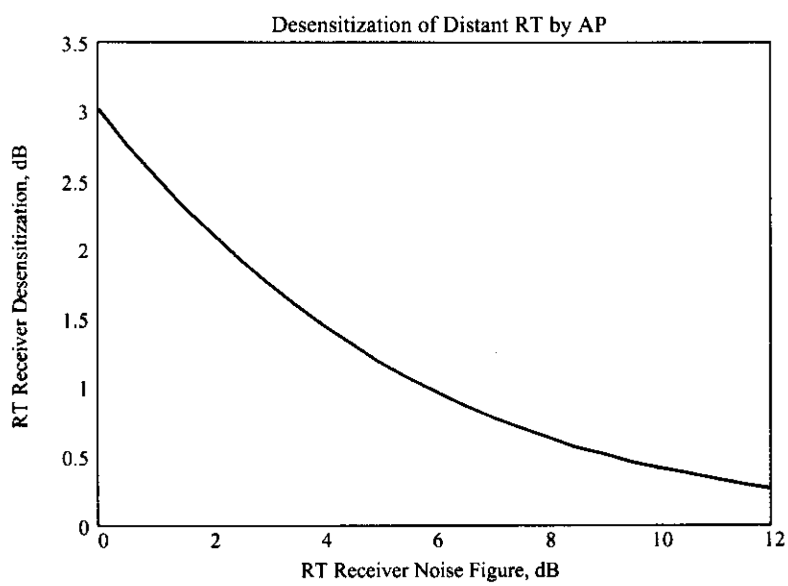
3.1.1 Transmitter Spectral Requirements: Ultimate Noise Floor

As supported in the previous section (3.1), the present IEEE802.11a spectrum mask can result in substantial receiver desensitization for relatively co-located independent networks. Since the ultimate noise floor is only required to be -40 dBr relative to the modulation main-lobe in [2], -the problem could exist regardless of the RF channel selected. The concern over the allowable transmitter output noise floor is further heightened by the likelihood that highly integrated products will be built to cover the entire 4.9 – 5.9 GHz range. Any bandpass filtering at the output of these wideband transmitters would most likely be completely ineffective in reducing the transmitted noise floor over the full 1 GHz of RF bandwidth.

The allowable output transmitter spectral noise floor can only be reduced so far before complexity and power consumption issues become severe. The adopted requirement must blend a measure of the multiple-network scenario performance improvement desired along with what is reasonable to achieve in a highly integrated low-cost monolithic 5 GHz RFIC.

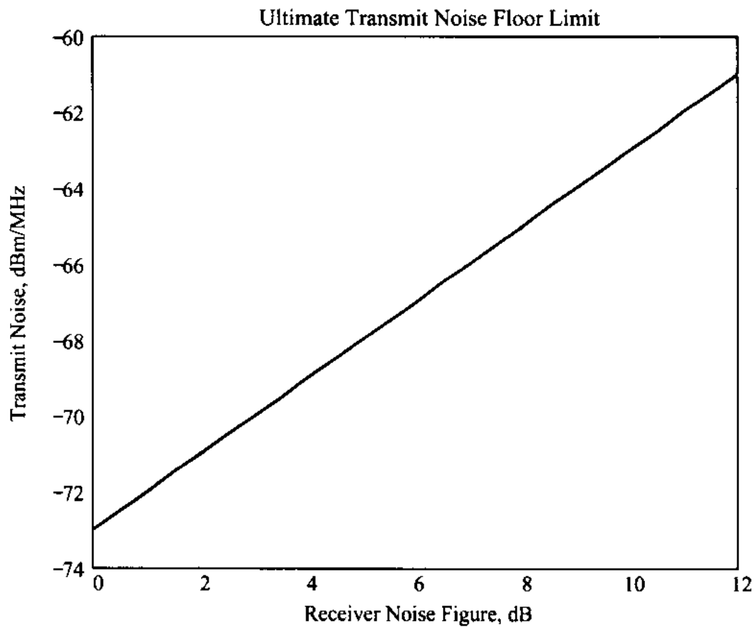
Different perspectives can be taken in order to determine the transmitter noise floor requirement that should be adopted as developed in detail in Section 9. In the first perspective, the transmitter noise floor at another terminal located R meters away is permitted to be equal to the ambient noise floor (-174 dBm/Hz). With this perspective, the distant terminal's loss in sensitivity due to the transmitter's noise floor will be as shown in Figure 3. If the nominal receiver noise figure for the terminal is assumed to be 8 dB, the loss in system sensitivity under this perspective is only about 0.6 dB which is certainly acceptable.

Figure 3 RT Receiver Desensitization When Constraining the Allowable Interference Level to Equal the Ambient Environmental Noise Level (See Section 9)



The second perspective developed in Section 9 addresses the much more demanding question, "Beyond what transmit noise floor performance level is no additional network benefit realized?" Quantitatively, the assumption is made that an interfering terminal is located only 1 meter away and a maximum sensitivity loss of 1 dB is allowed. The required transmit noise floor level under this perspective is as shown in Figure 4.

Figure 4 Permissible Transmit Noise Floor (dBm/MHz) for 1 dB Sensitivity Loss at 1 Meter Range



The final perspective addressed in Section 9 considers what transmitter output noise level is reasonable to achieve in a fully monolithic 5 GHz transceiver implementation. Although the argument presented there is fairly simple, it illustrates that the recommended transmit noise floor level should be achievable.

Recommendation Group 1:

1. **The transmitter output noise floor for frequency offsets greater than 30 MHz should be improved from the present -40 dBr (See Figure 1) to -47 dBm/MHz[5].**
2. **The transmitter output noise floor for frequency offsets greater than 30 MHz should exhibit further reduction as the transmitter output power level is reduced, ideally dB for dB until the limit specified in item (3) is achieved.**
3. **There is no need to reduce the transmitter output noise floor below -65 dBm/MHz for frequency offsets greater than 30 MHz.**

These requirements are recommended for the new 255MHz band and it is further recommended that these same requirements be adopted over time for the present U-NII band frequencies because all wireless users will benefit from the tighter spectrum requirements.

[5] The -47 dBm/MHz corresponds to -61dBr at a transmitter output power level of 27 dBm. At this transmitter output power level, this more demanding requirement represents a reduction in the allowable transmitter output noise level by 21.8dB compared to existing IEEE802.11a specifications for frequency offsets greater than 30 MHz.

3.2 *Transmit Power Control*

The rulemaking proposal in question [1] advocates provision for only 6dB of transmit power control range in the RLAN transmitters. In dense deployment situations like apartment and condominium complexes, this would result in a severe limitation on the number of simultaneous users that could be present in the 5 GHz band while delivering any meaningful level of QoS as needed for most if not all A/V applications. Furthermore, most user wireless links will be very asymmetrical (different down-link versus up-link throughput requirements) in terms of throughput and the opportunity to use less transmit power for the lower throughput links would also be lost resulting in more spectrum congestion than necessary.

If adequate transmit power level control is provided in each RLAN device, it is possible to re-use the same RF channel again thereby greatly expanding the number of users and the total throughput capacity supportable within a given geographical area. Without adequate transmit power control range, in many cases only N users within an apartment complex will be able to deliver QoS-quality wireless streams where N is the total number of RF channels available (presently 8 in the United States, 4 in Japan). More efficient usage of the limited RF bandwidth is beneficial to everyone. Additionally, by minimizing the transmit power, the ability of "hackers" to receive the signal will be reduced. While this is no substitute for strong security measures built into wireless protocols, it is well known that few consumers actually utilize even the minimal security measures built into today's RLANs. Gone are the days that having this additional control is "too costly" or "too complicated".

> ***Transmit power control is crucial if frequency re-use is to be a reality in the 5 GHz band for reasonably spaced networks.***

3.2.1 Minimum Transmit Power Level

The maximum useable transmit power level is dictated by existing FCC Part 15 rules. In addition, each RLAN terminal should be capable of dynamically adjusting its transmit power level to the minimum level necessary to have reliable communication for the throughput rate and range involved for a specific link. Transmit power adjustments in 2dB steps are recommended.

As argued in Section 10, each RLAN terminal must be capable of achieving a prescribed minimum transmit power level in order to ensure that the same RF channel can be re-used within a specific proximity to another RLAN network without causing that network undue interference. If the close-proximity distance is assumed to be R= 10 meters, the resulting required minimum transmit power level required[6] to satisfy (11) in Section 10 is -27dBm.

Radio signal absorption through walls and interior décor will generally be higher than free-space propagation loss. When these additional loss mechanisms are present in a given locale, the same RF channel may be re-used when the RLAN terminals are spaced more closely than 10 meters.

Devices that want to join a network may be unable to hear the other network devices if they are operating at a power level that is just sufficient for the existing network devices to communicate. In the case of CSMA-based network devices, they must be allowed to use their maximum transmit power level periodically in order to join the network. It is recommended that these high-power "probing" efforts should be done with a maximum duty factor of 1% with a burst length of 2 msec maximum in order to avoid interfering with other networks that may be operating close by on the same RF channel. Similar "probing" efforts by a TDMA network device should likewise abide by the same duty cycle and burst length constraints.

[6] Assuming □= 0.057 meters corresponding to a radio frequency of 5.26 GHz

Recommendation Group 2:

1. **In order to minimize the physical separation required between RLAN networks operating on the same RF channel so that negligible interference to each neighboring network results thereby maximizing RF channel re-use within any given locale, RLAN terminal devices should dynamically adjust the transmit power level used.**
2. **The transmit power level used should be the minimum level required for good data payload delivery over the range and at the throughput rate required.**
3. **Each RLAN terminal's transmitter should be able to adjust its output power level between a minimum level no higher than –27 dBm and the terminal's maximum output power level is 3dB steps (maximum, 2dB steps preferred).**
4. **Full-power "probing" activities conducted by network devices desiring to join a network should be limited to a maximum burst-length of 2 msec and a duty cycle of 1% in order to minimize interference to other networks that may also be using the same RF channel.**

3.2.2 Allowable Interference to Primary Services

With adequate control of the transmitter power level, negligible interference will occur for the proposed primary users like weather radar. The question that must be addressed is, "How much transmit power can be used by a RLAN transmitter without interfering with the primary service?" This question is addressed in Section 11. In summary, there must be an RLAN transmit power level below which completely negligible interference is imposed upon a primary service system like a weather radar. Using the reasoning presented in Section 11, the following example is provided.

Example 4:

Assume that the weather radar is using a transmit power level of 50 kilowatts and its receiver noise figure is 3 dB. If the weather radar signal level measured at the RLAN terminal corresponds to -64 dBm in 1 MHz bandwidth, equation (18) in Section 11 predicts that an acceptable RLAN terminal transmit power level of 30 dBm/MHz could be used resulting in interference to the weather radar that is just discernable. In the case of the IEEE802.11a waveform that has a modulation bandwidth of approximately 16.6MHz, this corresponds to an allowable RLAN transmitter output power level of 42.2dBm.

The variants in this simplistic argument are many because radar pulse-width, transmit power level, etc. all affect the outcome of equation (18) in Section 11. Even so, it is highly desirable that a RLAN network only be forced to vacate a radar-occupied channel if it needs to use a transmit power level above a certain limit. The present rulemaking proposal [1] assumes that RLAN transmitters will all be using essentially the same transmit power level rather than employing network-range-appropriate transmit power levels as advocated in this discussion.

Recommendation Group 3:

1. **The proposed rule change advocates using a measurement threshold of -62 dBm or -64 dBm depending upon the terminal's upper transmit power limit as the criteria to use or vacate a specific RF channel in deference to other primary services. If, for example, a given RLAN is using a maximum transmit power level of 0 dBm at the time, it is unreasonable to force this RLAN to vacate the channel when it is using a power level 23dB below the terminal's upper power limit.**
2. **It is therefore recommended that a soft back-off transmit power level rule be adopted whereby RLAN terminals capable of measuring receive power levels below -64 dBm be allowed to remain on the RF channel in question so long as they utilize a maximum transmit power level given by $P_{\max} = 23dBm - \left(P_{Measure} + 62dBm\right)$ where $P_{Measure}$ represents the RLAN terminal's power measurement of the suspected radar signal.**

3.3 Dynamic Frequency Selection (DFS)

Distinction needs to be made between a network identifying an available channel at first power-up and ongoing channel availability checking once a network is on-line. This is particularly true of TDMA networks in that once the network master has identified a clear channel for use, it normally broadcasts a beacon burst once every MAC frame thereby providing network coordination information for any other network device that may desire to join the network. The difference in perspective between an asynchronous CSMA-based MAC and a synchronous TDMA-based MAC are described in additional detail in Section 3.3.2.

3.3.1 Initial Dynamic Frequency Selection

Initial DFS (IDFS) refers to the first time after power-up that a network device is searching for an available channel or if the RF network has been inactive for more than a specified length of time. IDFS takes on a somewhat different role depending upon whether the network MAC is CSMA-based or TDMA-based.

In the absence of any network elements, a TDMA-based system can in principle choose to go into a hibernate mode where the normal MAC frame beacon signaling is suspended for a number of frame times or even seconds. This is done to minimize the average power used by the device. Each time a TDMA-based system is powered-up or returns from such a hibernate mode, it must perform a channel availability check similar to that done by a CSMA-based system. In the present context, IDFS will be taken to apply for TDMA-based systems whenever (i) initial power-up of the network is done, or (ii) whenever the network master has gone into a hibernate mode where it has not been listening to the RF channel for more than 100 msec.

CSMA-based systems utilize a "listen before talk" criteria as a fundamental concept of the MAC protocol and it is therefore natural to extend this same concept to perform the IDFS function before every burst by a CSMA-based terminal device.

Whether a wireless network is CSMA-based or TDMA-based, the IDFS method used should guarantee with high confidence that the RF channel adopted by the network does not pose interference issues for primary services that may also be using the same RF channel (e.g., weather radar). A more effective means to specify the requirements for both IDFS and on-going DFS (ODFS) is presented in the following section.

3.3.2 Ongoing Dynamic Frequency Selection (ODFS)

The proposed rule changes regarding DFS, specifically the *Channel Availability Check Time* and the *Channel Move Time* as written do not ensure that the primary services will be protected as desired, and yet the *Channel Availability Check Time* imposes an onerous requirement (particularly for CSMA-based systems) to wait 60 seconds before transmitting. A far more effective and efficient guideline would be to require a network to simply determine that a radar signal is not present on the RF channel in question with a specified confidence level (e.g., 99%) before adopting the RF channel for its networking activities. Adopting this type of guideline would leave far more flexibility in the hands of system architects while achieving the desired end-result more reliably.

The proposed rule change involving a *Non-occupancy Period* of at least 30 minutes following the detection of an on-channel radar system should be re-cast in a similar manner based upon detection confidence levels. As presently drafted, even one false radar system detection per half-hour would mandate that the RF channel in question never be used thereby representing a steep penalty if a suspected detection is actually false. It is impractical to require each RLAN device or network master to analyze every detected signal and effectively classify it as a radar signal, another IEEE802.11a or HiperLAN2 signal, a ultra-wideband (UWB) signal, a rogue one-time interference, etc. because of the cost and complexity issues involved.

In the situation where a new network is being brought on the air, it is reasonable to require a minimum Channel Availability Check Time corresponding to the slowest nominal radar scan rate used in this service, but beyond this limit the confidence level criteria should be adopted based upon the radar parameters already described in the rulemaking proposal.

The "listen before talk" model discussed in the proposed rule change regarding DFS applies primarily to a CSMA-based network because this same mechanism is used as an integral part of the CSMA underlying concept. In contrast, a TDMA-based network inherently employs a synchronous frame structure typically having a length of 1 msec to 2 msec for 5 GHz applications and the centralized master terminal routinely listens for new terminals that wish to join the network during every frame. Since TDMA-based systems effectively listen "before" and "after" every transmission and these transmissions by the master terminal occur every 1 msec to 2 msec, the "listen before talk" concept is really an artifact of CSMA-based networks since TDMA-based networks are effectively "always listening".

Recommendation Group 4:

1. **Channel availability checks should be based upon guaranteeing a specified degree of confidence (e.g., 99%) that a radar signal is not present in the same RF channel rather than resorting to a strictly time-based approach as presented in the present rulemaking proposal.**
2. **IDFS activities should be conducted for a minimum length of time corresponding to the nominal radar scan rate but otherwise based upon confidence level.**
3. **If a radar signal is detected within a given RF channel, the RLAN should still be able to adopt that RF channel for use so long as (i) the RLAN terminal devices all have transmit power level control capability as**

described in Section 3.2, and (ii) the maximum transmit power level used by any RLAN terminal devices complies with the second item specified in Recommendation Group 3.

3.3.3 Other DFS-Related Considerations

Although not stipulated in the proposed rulemaking material, it is highly recommended that a specific 20MHz-based channelization plan be provided in the FCC rules. This action would improve the reliability of the IDFS and ODFS measurement activities thereby improving an RLAN's ability to minimize interference to other primary service users in the 5 GHz band.

3.4 Channel Usage Efficiency

A common theme throughout this rulemaking comment memorandum is to adopt rules that lead to the greatest utilization of the 5 GHz resources available. Historically, wireless networking has primarily been done using CSMA-based networks that guarantee no QoS, but with the demands posed by A/V-centric CE devices for good QoS performance, it is necessary to adopt rules that prevent non-QoS-centric networking applications from seriously interfering with QoS-centric applications and visa versa. Rules pertaining to (a) transmit power level control, (b) improved transmit spectrum noise sidebands and (c) IDFS and ODFS all seek to achieve greater utilization of the 5 GHz spectrum.

High-QoS performance automatically implies that the network packet error rate (PER) is reasonably low and consequentially, re-transmission of errant data packets is fairly infrequent. If for example, the PER is 50% for a given link, twice the network RF channel resources are required to deliver the same data payload compared to a system enjoying a PER of 0%. Some non-zero PER must be allowed in any practical RF system but some constraint should be applied to any 5 GHz wireless network in order to share the RF channel as efficiently as possible with other potential networks.

Example 5:

Assume that a network is operating on a given RF channel and that the link performance characteristics shown in Table 1 apply.

Table 1 Example RF Link Performance with Different PHY Modes

Link	Signaling Rate, Mbps	IEEE802.11a PHY Mode	Required SNR at Receiver, dB[7]	Observed PER	Net Payload Throughput Rate, Mbps[8]
1	54	64QAM ¾	27	45%	23.76
2	48	64QAM 2/3	26	40%	23.04
3	36	16QAM ¾	22	30%	20.16
4	24	16QAM ½	16	5%	18.24

As evidenced in the far right-hand column of Table 1, the cost in achieving the last few Mbps of payload throughput involves incurring very high PER levels along with the need to use high transmitter output power in order to deliver the required SNR values corresponding to the higher

[7] Sensitivity values from IEEE802.11a standard for an AWGN channel
[8] Assumes system throughput efficiency of 80% due to overhead factors

signaling rates. The observed non-zero PER levels are due primarily to channel multipath and it is assumed that no collisions are present if the system uses a CSMA-based MAC.

In comparing Link #1 and Link #4 in Table 1, it may seem acceptable to use the Link #1 PHY mode to achieve the highest throughput rate when the network is considered in isolation. However, if the location of the network is in an apartment complex where many users have separate networks vying for RF spectrum, further consideration must be given. Comparing these two link scenarios side by side, Link #1 requires (a) a SNR that is 11 dB higher while also (b) transmitting roughly 82% more bits per unit of time in order to deal with all of the packet re-transmissions involved with the high PER. Not only is the Link #1 transmitter broadcasting over the air with a duty cycle roughly 82% higher than the Link #4 case, but its signal "footprint" extends 11 dB further in range before the same RF channel can be re-used by another network. The complaint is not that the user needs 21 Mbps to transport their US-HDTV signal across the network but rather that the rare spectrum resources are being used with such inefficiency.

When spectrum resources will be potentially quite rare in dense housing situations like apartment complexes, it is not at all unreasonable to require that RLANs operate with a specified measure of spectrum resource efficiency. In terms of interference imposed on other networks, the only resource measures available are (i) receive signal to noise ratio (SNR) required for a link, and (ii) the average duty cycle required during the transmissions to achieve the required payload throughput. Since good transmit power level control is ultimately responsible for delivering most of the receive SNR observed, the real metric that indicates the RF channel usage efficiency is the PER.

A second very important factor to consider regarding RF channel utilization efficiency is the role that frequency-selective multipath plays. The receiver sensitivity SNR values used in Table 1 only apply to an additive white Gaussian noise (AWGN) channel whereas most if not all indoor environments exhibit potentially severe frequency-selective fading. The net result for an indoor networking system is that some systems will be forced to use a high transmit power level in order to communicate over even a very short range such as within a single family room. Short of doing fairly exotic ranging and other signal processing in order to assess the role of multipath in the link performance, which is impractical due to the associated cost and complexity, the best metric to use is again PER. Under severe multipath conditions, even the maximum transmit power level will be unable to reduce the PER and yet if left unattended to, this struggling network would be permitted to extend a very large signal footprint in range thereby preventing any re-use of the channel for a substantial distance.

Recommendation Group 5:

1. **Recognizing that RF spectrum resources are rare and that channel re-use must be available in dense deployment situations like apartment complexes, a measure of channel-use efficiency should be employed to ensure that struggling networks do not consume a disproportionate amount of the available resources.**
2. **One of the most readily available metrics for channel-use efficiency assessment is the PER and this should be adopted as the metric of choice.**
3. **Network links should be constrained to use a signaling rate no higher than that for which the average PER is less than or equal to 15% thereby ensuring good efficiency while also accommodating reasonable packet re-transmission activity for data packets received in error.**

4. Summary

A number of the recommendations presented in this memorandum (e.g., transmit power level control, dynamic frequency selection) echo the sentiments of other standards bodies like HiperLAN2 in Europe. The arguments in favor of these additional provisions are fundamentally inescapable and should therefore be adopted if only to keep parity with other standards and governing bodies. All wireless networking participants benefit if the correct guidelines are adopted.

The potential for A/V networking in the 5 GHz band is compelling. The FCC rules should reflect the needs of QoS and non-QoS networks equally in that one network type should not prevail to the detriment of the other. With the advent of complete systems-on-chip, the difficulties involved with implementing the recommendations herein are very minimal.

Although the recommendation for a minimal measure of channel-use efficiency may seem new, governing bodies routinely administrate guidelines for the use of commonly-shared limited resources. Just as the EPA mandates certain emission limits for our air and minimum average gasoline car mileage for Detroit, the pervasive nature of wireless networking combined with the maturity of wireless technology should force the guidelines to be forward-looking in establishing minimal performance metrics like the PER-based recommendation presented earlier.

5. Acronyms Used

Table 2 Table of Acronyms

Acronym	Meaning
AP	Access Point
AWGN	Additive White Gaussian Noise
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DFS	Dynamic Frequency Selection
EPA	Environmental Protection Agency
FCC	Federal Communications Commission
IDFS	Initial DFS
MAC	Medium Access Control
ODFS	Ongoing DFS
OEM	Original Equipment Manufacturer
OFDM	Orthogonal Frequency Division Multiplex
PA	Power Amplifier
PER	Packet Error Rate
QoS	Quality of Service
RLAN	Radio Local Area Network
RT	Remote Terminal
TDMA	Time Division Multiple Access
US-HDTV	High Definition Television (United States)
UWB	Ultra-Wideband

6. References

1. "Notice of Proposed Rulemaking, In the Matter of Revision of Parts 2 and 15 of the Commission's Rules to Permit Unlicensed National Information Infrastructure (U-NII) Devices in the 5 GHz Band", FCC 03-110, Released June 4, 2003, ET Docket No. 03-122, RM-10371
2. IEEE802.11a Specification
3. Broadband Radio Access Networks (BRAN), HIPERLAN Type 2, Physical (PHY) Layer Specification, ETSI TS 101-475
4. "Dynamic Frequency Selection (DFS) in Wireless Access Systems (WAS) Including Radio Local Area Networks (RLAN) for the Purpose of Protecting the Radiodetermination Service in the 5 GHz Band", ITU, Document 8/152-E, 31 January 2003

7. Appendix I: Technical Details for Section 3.1

In the case where both the Access Point (AP) and Remote Terminal (RT) are using omni-directional antennas with 0 dBi gain, the Friis formula can be used to compute the signal level received at the RT (over a free-space channel) as

$$P_{RT\_Rx} = P_{Tx}\left(\frac{\lambda}{4\pi R}\right)^2 \tag{1}$$

where is the wavelength in meters, R is the distance between the AP and RT in meters, and P_{Tx} is the AP transmit power in Watts. In the case where the modulation bandwidth is taken to be 16.6 MHz and the RT receiver noise figure is 8 dB, the minimum detectable signal (MDS) is given by

$$\begin{aligned} MDS_{dBm} &= -174 + NF_{dB} + 10Log(16.6MHz) \\ &= -94dBm \end{aligned} \tag{2}$$

In terms of a spectral density per MHz, $MDS_{MHz\_dBm} = -106\, dBm$. Continuing, if the AP transmitter output spectrum is given by the mask in Figure 1 and the total transmit output power is given by P_{Tx_dBm}, the allowable transmit noise floor (per MHz) for frequency offsets > 30 MHz is given by

$$\begin{aligned} P_{Floor\_dBm/MHz} &= P_{Tx\_dBm} - 10Log(16.6) - 40 \\ &= P_{Tx\_dBm} - 52 \quad dBm/MHz \end{aligned} \tag{3}$$

The permissible transmitter output noise floor given by Figure 1 leads to receiver desensitization for any RT that is in reasonably close geographical proximity to the AP and yet part of another network.

8. Appendix II: Technical Notes Supporting Figure 2

In the case where both the Access Point (AP) and Remote Terminal (RT) are using omni-directional antennas with 0 dBi gain, the Friis formula can be used to compute the signal level received at the RT (over a free-space channel) as

$$P_{RT\_Rx} = P_{Tx}\left(\frac{\lambda}{4\pi R}\right)^2 \tag{4}$$

where is the wavelength in meters, R is the distance between the AP and RT in meters, and P_{Tx} is the AP transmit power in Watts. In the case where the modulation bandwidth is taken to be 16.6 MHz and the RT receiver noise figure is 8 dB, the minimum detectable signal (MDS) is given by

$$\begin{aligned} MDS_{dBm} &= -174 + NF_{dB} + 10Log(16.6MHz) \\ &= -94dBm \end{aligned} \tag{5}$$

In terms of a spectral density per MHz, $MDS_{MHz\_dBm} = -106\, dBm$. Continuing, if the AP transmitter output spectrum is given by the mask in Figure 1 and the total transmit output power is given by P_{Tx_dBm}, the allowable transmit noise floor (per MHz) for frequency offsets > 30 MHz is given by

$$\begin{aligned} P_{Floor\_dBm/MHz} &= P_{Tx\_dBm} - 10Log(16.6) - 40 \\ &= P_{Tx\_dBm} - 52 \quad dBm/MHz \end{aligned} \tag{6}$$

The permissible transmitter output noise floor given by Figure 1 leads to receiver desensitization for any RT that is in reasonably close geographical proximity to the AP and yet part of another network.

Assuming free-space propagation between the AP and RT involved, the amount of receiver desensitization due to the AP's noise floor is given by

$$\Delta S_{dB} = 10Log\left[1 + 10^{0.1\left(P_x - MDS_{MHz\_dBm}\right)}\right] \tag{7}$$

where

$$P_x = P_{Tx\_dBm} - 10Log(16.6) - 40 + 20Log\left(\frac{\lambda}{4\pi R}\right) \tag{8}$$

The loss in RT sensitivity due to the AP's noise floor is shown versus AP-to-RT separation and AP transmit noise power in Figure 2.

9. Appendix III: Perspectives on Transmit Noise Floor Limits

Perspective 1: Transmitter Noise Floor at Distant RT Equal to Ambient Noise Floor

The ultimate limit for the transmitter output noise floor is dictated by the proximity of the RT to the AP and the amount of receiver desensitization that is acceptable. Stipulating now that the noise floor from any transmitter under any circumstances shall not be greater than the ambient noise level (-174 dBm/Hz) at a distance of 10 meters from the transmitter[9], the transmitter output noise power spectral density must be reduced to

$$-174\frac{dBm}{Hz}+20Log\left(\frac{4\pi R}{\lambda}\right)+60\frac{dBHz}{MHz}=-47\frac{dBm}{MHz} \qquad (9)$$

Under this noise limit criteria, an RT located 10 meters away from the AP would experience a degree of receiver desensitization, the amount being dependent upon the RT receiver's noise figure. This calculation is shown graphically in Figure 3.

Perspective 2: Transmitter Noise Floor Limit for Network Benefit

It makes no difference to attempt to improve the transmitter's output noise floor beyond a certain point. The point adopted for this discussion is the noise level at which an RT positioned 1 meter away from an AP experiences a maximum of 1 dB of system sensitivity loss. Assuming unity-gain transmit and receive antennas for the AP and RT, the allowable transmit noise floor to meet this 1 dB criteria is given by

$$P_{dBm/MHz}=10Log\left[\left(\frac{4\pi}{\lambda}\right)^2\left(10^{0.1(-174+NF_{dB}+1)}-10^{0.1(-174+NF_{dB})}\right)\right]+60\frac{dB}{MHz} \qquad (10)$$

and this result is shown graphically in Figure 4. As shown there, there is no need to reduce the transmitter output noise floor below approximately -65 dBm/MHz in the case where the RT receiver noise figure is taken to be 8 dB.

Perspective 3: Practical Transmitter Output Noise Floor for Monolithic Implementations

In most monolithic 5 GHz product implementations, spectral components at frequency offsets between 11 MHz and 30 MHz in Figure 1 are due to third-order nonlinearities in the transmit chain and to a much less degree system phase noise. Although not stipulated explicitly in [2] because this standard does not include transmit power level control, ideally the transmitter output noise floor should reduce as

[9] Assuming unity-gain RT and AP antennas

the transmit power level is reduced at least to a level where it poses very little desensitization to other RT units that may be located even nearby the AP (i.e., the limit suggested in Perspective 2).

In a monolithic up-converter, most of the broadband noise will originate from the quadrature mixer and that noise will be amplified through the transmit chain until it appears at the transmitter output. For discussion purposes, assume that the effective noise figure of the quadrature mixer is 20 dB and that the mixer's 1 dB output compression point is 0 dBm. Owing to the rather severe linearity needs imposed by OFDM, further assume that the signal level at the quadrature mixer is kept 10 dB below the compression point or equivalently -10 dBm. In the case where the AP transmitter output power level is 200 mW, the transmit chain including the power amplifier must provide 33 dB of additional power gain. Under this set of assumptions, the transmitter output noise level due to the quadrature mixer would be -174 dBm/Hz + 20dB + 33dB + 60dB/MHz = -61dBm/MHz. Since this example results in an output noise floor that is considerably better than the -47 dBm/MHz guideline suggested in Perspective 1, monolithic construction of transmitters delivering the improved noise performance should be readily achievable.

10. Appendix IV: Minimum Transmit Power Level

The maximum useable transmit power level is dictated by existing FCC Part 15 rules. In addition, each RLAN terminal should be capable of dynamically adjusting its transmit power level to the minimum level necessary to have reliable communication for the throughput rate and range involved. Transmit power adjustments in 2dB steps are recommended.

Each RLAN terminal must be capable of achieving a prescribed minimum transmit power level in order to ensure that the same RF channel can be re-used within a specific proximity to another RLAN network without causing that network undue interference. While signal propagation losses will vary widely with the building construction type and interior decor involved, free-space propagation will be assumed in order to remain conservative. Assuming that the RLAN terminals are employing unity-gain antennas, the received signal power at another terminal is given simply as

$$P_{Rx\_dBm} = P_{Tx\_dBm} - 20Log\left(\frac{4\pi R}{\lambda}\right) \qquad (11)$$

where R is the distance between the RLAN terminals in meters, λ is the signal wavelength in meters, P_{Tx_dBm} is the minimum transmit power level achievable by an RLAN terminal, and P_{Rx_dBm} is assumed to be the minimum detectable signal level which is given by

$$\begin{aligned} P_{Rx\_dBm} &= -174 + NF_{dB} + 10Log(16.6MHz) \\ &= -101.8dBm + NF_{dB} \end{aligned} \qquad (12)$$

Assuming that the RLAN terminal receivers have a noise figure of 8dB, the minimum detectable signal level is P_{Rx_dBm}= -93.8dBm. If the minimum distance between the RLAN terminals which are members of different RLAN networks attempting to use the same RF channel is assumed to be R= 10 meters, the resulting required minimum transmit power level required[10] to satisfy (11) is -27dBm.

Radio signal absorption through walls and interior décor will generally be higher than free-space propagation loss. When these additional loss mechanisms are present in a given local, the same RF channel may be re-used when the RLAN terminals are spaced more closely than 10 meters.

[10] Assuming λ= 0.057 meters corresponding to a radio frequency of 5.26 GHz

11. Appendix V: Allowable Interference with Primary Services

A fairly simple guideline to answer this question can be derived from the basic radar range equation as follows. Assume that normal free-space signal propagation is involved and that the RLAN terminals are all utilizing unity-gain antennas. In this case, the radar signal strength measured by an RLAN terminal's receiver is given by

$$P_{Rx\_L} = \frac{P_{Tx\_W} G_W}{4\pi R^2} A_{e\_L} \tag{13}$$

where

P_{Tx_W} = Transmit Power of Weather Radar, Watts
G_W = Numerical Antenna Power Gain of Weather Radar
R = Distance Weather Radar to RLAN, meters

and the effective aperture represented by the RLAN terminal's unity-gain antenna is given by

$$A_{e\_L} = \frac{\lambda^2}{4\pi} \tag{14}$$

where is the wavelength of the signal in meters. Upon substitution of (14) into (13), the power relationship for the weather radar-to-RLAN terminal is given simply by

$$P_{Tx\_W}\, G_W \left(\frac{\lambda}{4\pi R} \right)^2 = P_{Rx\_L} \tag{15}$$

The signal propagation losses in the reverse direction (RLAN terminal-to-weather radar) will be the same as the losses associated with (15). Therefore, the signal power received by the weather radar from the RLAN terminal's transmitter can be expressed as

$$P_{Rx\_W} = \frac{P_{Tx\_L}}{4\pi R^2} A_{e\_W} = P_{Tx\_L}\, G_W \left(\frac{\lambda}{4\pi R} \right)^2 \tag{16}$$

In order to complete the argument, it is necessary to compare the RLAN-related interference to the radar with a meaningful quantity, in this case the minimum detectable signal at the radar receiver input which can be expressed by

$$MDS_{W\_dBm} = -174 + NF_{dB} + 10Log(BW) \tag{17}$$

where NF_{dB} is the noise figure of the weather radar receiver and BW is the bandwidth of the radar waveform in Hertz. If the RLAN-related interference is allowed to just equal the minimum detectable signal at the radar receiver input, upon combining (16) and (15) leads to the sought after relationship between system parameters of

$$P_{Tx\_L} = MDS_W \frac{P_{Tx\_W}}{P_{Rx\_L}} \tag{18}$$